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Abstract

The combination of resonant laser ionization, nuclear spectroscopy and mass measurements allows the deconvolution of the low-energy structure of atomic nuclei. Three β-decaying isomers of ^{70}Cu have been unambiguously identified with the Penning trap mass spectrometer ISOLTRAP. In addition, isomerically pure ensembles of the short-lived radionuclides ^{68,70}Cu have been prepared.

1 Introduction

For the first time we have demonstrated that element-selective laser ionization in combination with high resolution mass spectrometry can be used to prepare isomerically pure beams of ^{68}Cu and ^{70}Cu. To this end, the resonance ionization laser ion source (RILIS) [1] and the triple-trap mass spectrometer ISOLTRAP [2, 3] at ISOLDE/CERN [4] were used. Together with β–γ coincidence studies this method allowed us to determine the low-energy structure of ^{70}Cu and to unambiguously identify three β-decaying isomers. By selective laser ionization and high-resolution Penning trap mass measurements it was possible to identify each state and to determine its mass with a relative uncertainty of $\delta m/m \approx 5 \cdot 10^{-8}$. Thus, a clear identification was possible, which allowed us to resolve the assignment puzzle in ^{70}Cu [5].

2 Experimental Procedure

2.1 Production and Ionization of Radionuclides at ISOLDE

The short-lived radionuclides are produced at the on-line isotope separator ISOLDE [4] by bombarding a thick target of a few g/cm^2 with 1.4-GeV proton pulses containing in average about $3 \cdot 10^{13}$ protons. The exotic nuclides diffuse out of the target, which is heated up to 2000°C and are ionized either by surface, plasma or resonant laser ionization. The 60-keV ion beam is then mass-separated in a magnetic separator and delivered to different experiments.

For the work presented here the laser ion source was applied. The atomic excitation path for the copper isotopes is shown in Fig. 1. It is a resonant excitation scheme followed by ionization through a strong autoionizing (AI) resonance. Two copper vapor lasers with a repetition rate of 11 kHz are used to pump the frequency-doubled dye lasers. The bandwidth of the laser for the first transition at $\lambda = 327.4$ nm was 1.2 GHz, which made it possible to resolve the hyperfine structures of the ^{68,70}Cu isomers [6, 7]. For the ionization step a broadband (≈ 24 GHz) dye laser was used.

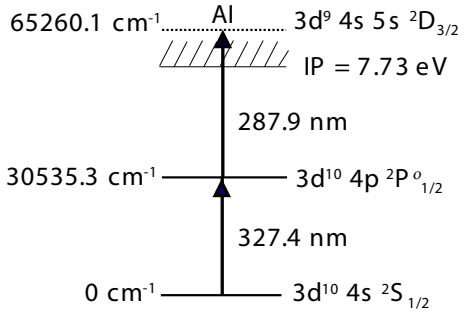

Figure 1: Excitation scheme used for double-resonance ionization of copper.

2.2 High-Precision Mass Measurements with ISOLTRAP

The mass measurements on the copper isotopes were performed with the Penning trap mass spectrometer ISOLTRAP [2, 3]. It measures the mass m of ions with charge q stored in a homogeneous and stable magnetic field B via the determination of the cyclotron frequency $\nu_c = qB/(2\pi m)$. As shown in Fig. 2 ISOLTRAP consists of three traps, a linear radiofrequency Paul trap [8] and two Penning traps [2] located in superconducting magnets with field strengths of 4.7 T and 5.9 T, respectively. The first two traps are operated with helium

buffer gas and serve for deceleration, cooling, bunching and isobar purification of the continuous 60-keV ion beam delivered by ISOLDE. The third trap is a precision Penning trap for the mass measurements. The ions' cyclotron frequency ν_c is probed by excitation of the ions' motion with a radiofrequency signal [9] and measurement of the time of flight to the micro-channel-plate detector MCP5. The cyclotron resonance (see inset of Fig. 2) is determined by repetition of this sequence and measurement of the time of flight as a function of the frequency of the applied field. The magnetic field strength B is determined via the cyclotron frequency of the well-known $^{85}Rb^+$ mass for the presented copper measurements. In total, the masses of close to 300 radionuclides have been measured by use of ISOLTRAP with a relative uncertainty of typically $\delta m/m = 10^{-8} - 10^{-7}$ [10].

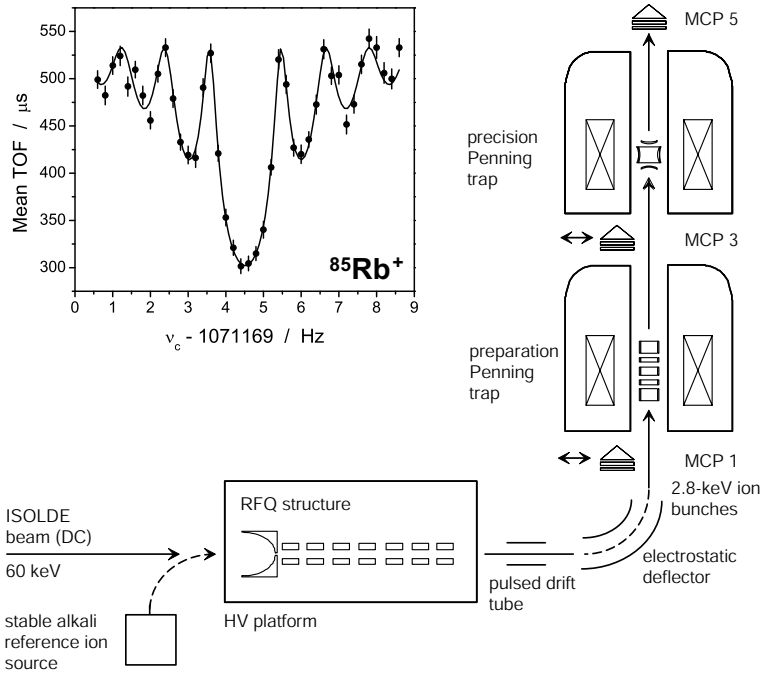

Figure 2: Schematic drawing of the mass spectrometer ISOLTRAP including the RFQ trap and the preparation and precision Penning traps. Micro-channel-plate (MCP) detectors are used to monitor the ion transfer (MCP1 and MCP3) as well as to record the time-of-flight resonance (MCP5) for the determination of the cyclotron frequency. The inset shows a cyclotron resonance for $^{85}Rb^+$ which was used here for the magnetic-field calibration. The line is a fit of the theoretical curve to the data points [11].

2.3 Preparation of Isomerically Pure Ensembles

Due to the broad bandwidth and thus the overlapping hyperfine structure the selectivity of the RILIS was not sufficient to separate the ^{70}Cu isomers effectively. A cyclotron excitation time of $T_{\mathrm{RF}} = 0.9\,\mathrm{s}$ was used in the precision Penning trap. This results in a linewidth of $\Delta\nu_{\mathrm{c}}(\mathrm{FWHM}) \approx 0.9/T_{\mathrm{RF}} \approx 1\,\mathrm{Hz}$ and a resolving power $R = \nu_{\mathrm{c}}/\Delta\nu_{\mathrm{c}}(\mathrm{FWHM})$ of more than $1 \cdot 10^6$, sufficient to clearly resolve the ^{68,70}Cu isomers. In order to avoid systematic errors it is not only important to resolve ions with different masses but also to selectively remove the unwanted species, as for instance remaining isobaric contaminations or isomers. This can be achieved with appropriate excitation of their motion. In the experiment presented here, radiofrequency cleaning excitation periods of 3 s were used to prepare isomerically pure ensembles.

3 Results and Discussion

By scanning the laser frequency of the first transition and by use of a $\beta\gamma$-coincidence setup the radionuclides were detected and identified [6, 12]. Investigation of the intensities of the individual γ-rays in the β-decay of ^{70}Cu revealed distinct groups of γ-rays belonging to three different hyperfine-structure patterns as shown in the top part of Fig. 3. This is a clear evidence for the existence of three β-decaying isomers in ^{70}Cu. Tentative spin values were deduced from the magnetic moments with spin (6^-) for the lowest, (3^-) for the intermediate and 1^+ for the highest lying isomer [7].

For the separation of the three isomers and the subsequent mass measurements the laser frequency was tuned to the positions (a, b, c, d) as indicated by arrows in the upper part of Fig. 3. The obtained cyclotron resonances are shown in the lower part of Fig. 3. For position a and d the selectivity of the RILIS did not suffice to prepare isomerically pure samples. Since the resolving power of ISOLTRAP is sufficient to clearly separate the different cyclotron resonances (see a in the lower part of Fig. 3), we applied the above mentioned mass selective cleaning procedure to one or two of the isomers to obtain an isomerically clean cyclotron resonance of the isomer of interest (see resonance d). For the positions b and c the selectivity of the laser ionization was high enough to obtain almost pure ensembles of the (6^-) and (3^-) isomer.

Since the cyclotron frequency is inversely proportional to the mass of the ion, our results unambiguously determined the order of the levels and assigned spins to states, *i.e.* the (6^-) is the ground state, the (3^-) the first and the 1^+ the second isomeric state, as proposed in [7]. The mass value differences are in excellent agreement with the excitation energies obtained in the decay studies

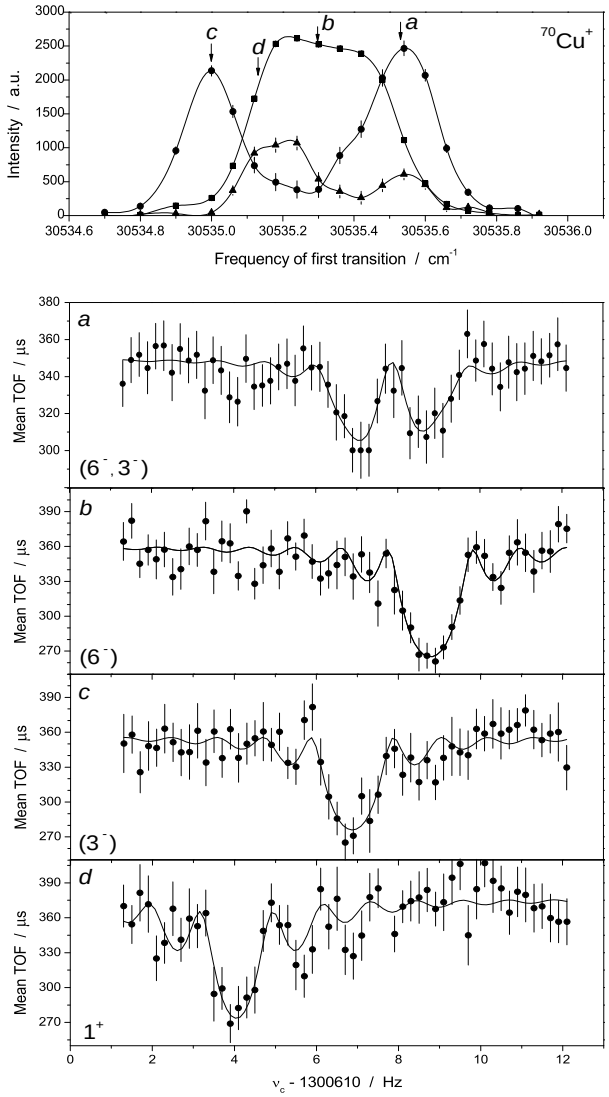

Figure 3: Top: Measured $(\beta - \gamma)$ radioactivity of the ground (squares), first (bullets) and second (triangles) isomeric state of $^{70}Cu^{+}$ versus laser frequency of the first transition. Bottom: Time-of-flight resonance curves as a function of cyclotron frequency for the laser settings marked with arrows (a, b, c, d) in the top figure. (a) shows the isomers resolved but not separated while $(b - d)$ shows the sequential *separation* of the isomeric states. The assignment of the different spin states to ground and isomeric states results from the ISOLTRAP measurement (see text). The tentative spin values were taken from [7]. The solid lines are fits of the theoretically expected line shape [11] for two (a) or one (b, c and d) resonance curves to the data points.

and are given in [5]. The same procedure was applied to ^{68}Cu to prepare pure ensembles of the ground and isomeric state and to perform background-free mass measurements.

These data exemplify the strength of the unique combination of resonance ionization and Penning trap mass spectrometry to produce isomerically pure ensembles of short-lived radionuclides. A further exploration of these techniques, including post-acceleration with *e.g.* REX-ISOLDE [13], will open a whole field of radioactive beam research with isomer beams.

Acknowledgments

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